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The optimal balance point between NRW reduction measures, full water costing and water pricing in water distribution systems. Alternative scenarios forecasting the Kozani's WDS optimal balance point

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Abstract

The paper summarizes the final outcome of a study that lasted three years and deals with NRW reduction measures, the FWC integration in water price and the consumers' response to water price changes. Each term of the above three, interacts with the others and a dynamic balance is formed. There is a point where this balance causes optimal (socially and economically fair) results for all urban water users. The implementation of the mechanism of finding the optimal balance point in Kozani's (a city in northern Greece) WDS under increased water price is presented.

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Keywords: Residential water demand; panel data; water price; elasticity of demand; full water cost

1. Introduction

In recent years many efforts have been observed to reduce real losses and the generally NRW. The problem is multifactorial because there are entering concepts like NRW reduction measures, such as pressure management, EARL levels, water pricing policies, conservative demand, full water costing etc. Also total water consumption

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consists of many components, the volume of which is affected differently by system's operating pressure and water price variation. PM is a strong leakage management tool [1-5]. It is widely known among water utility managers that PM leads to reduced leak flow rates and bursts repair costs for pipe [4-7].

Full water costing will lead water utilities to implement full water pricing. By integrating resource and environmental cost in WP, it will increase dramatically. The additional cost will be paid by the consumers unless water utilities implement other consumer relief policies. Through elasticity of water demand, the impact of WP increase to the variation of the water volume that yields revenue, can be measured. By using network's hydraulic model, it is possible to estimate the change of the rest SIV components and especially the real losses volume. At the first half of the methodology the consumers' and generally the system's response time to these price changes is eliminated. The new water balance of the system, which is result of price increase, will lead to a high reduction of residential water demand. The other SIV components (real losses, apparent losses, not billed, authorized consumption) will not change considerably as they depend mainly on the system's operating pressure, which doesn't change very much. Therefore the basic consequences of full water costing should be price increase and consumption (residential and commercial) reduction.

To avoid adverse implications of full water costing, water utilities must act decisively and improve the efficiency of water use. Measures which will reduce NRW volume should be taken. One of the two main strategies is PM implementation (the other is asset management), which yields significant economic benefits when the water network is characterized by high operating pressures. The methodology presented at the present study co-estimates the consumer's relief through NRW reduction at EARL levels. PM implementation at EARL levels will lead to an important SIV reduction, hence to an important FWC reduction. In case of a water system, whose full water cost increases along with its volume increase, this methodology results in reduced direct expenditures and thus, WP reduction. By pressure reduction though, the consumption is also reduced. It is important then to define the effects - both positive and negative- for the system and determine the point of optimal system balance not only for water price and full water cost but for all SIV components as well. The importance of finding the balance point of all system's factors is significant because the impact of WP increase in each one of SIV components and in full water cost is calculated in advance. In addition, the balance point between real losses and revenue water is estimated in advance giving the appropriate motivation for the water utilities to implement NRW reduction measures.

Nomenclature

CARL	Current Annual Real Losses
DEYAK	Water Utility of Kozani
EARL	Economic Annual Real Losses
ELL	Economic Level of Leakage
FWC	Full Water Cost
NPV	Net Present Value
NRW	Non-Revenue Water
SIV	System Input Volume
UARL	Unavoidable Annual Real Losses
WDS	Water Distribution System
WP	Water Price

2. The proposed methodology

The proposed methodology determines the balance point between all urban water uses, after the implementation of NRW reduction measures and the WP increase resulting from its full costing. The system's balance is disrupted because of the WP increase which will follow the FWC increase. Due to the elasticity of billed consumption, system's demand will decrease causing lower water abstraction and, finally, FWC reduction. Then follows WP reduction and consumption increase due to the price elasticity of water demand. This continuing variation of water

system's factors (including operating pressure) also includes the rest SIV components, namely real losses, illegal use, under-registration, non-billed authorized consumption etc. These repeated fluctuations do have converging extremes resulting in a zero step variation. Based on the new WP and the new FWC, ELL of pressure management is calculated. For this new optimal Water Balance, full water cost is recalculated and the above mentioned procedure is repeated. After a number of repeats, a balance point for all factors of Water Balance occurs. Type "A" MS Excel files calculate the final annual Water Balance in case of WP increase, taking under account the price elasticity of residential water demand and the subsequent variations of the SIV components. Type "B" MS Excel files calculate the SIV balance after the PM implementation at EARL levels for each water cost and water price variation. The results of the two file types are entering the central file M, as the results of this file B_i constitute the incoming data of the file A_i (Figure 1). After successive steps, the system balances.

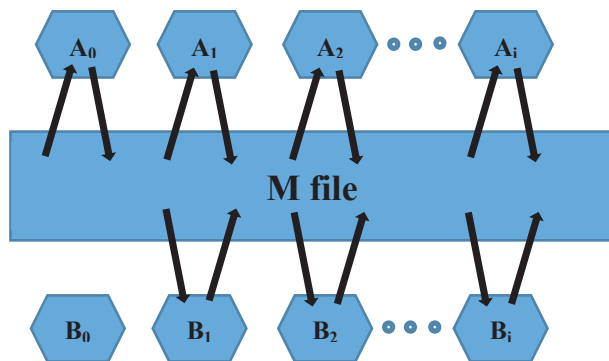


Figure 1. Interdependence of the files.

2.1. Tracking Files of system's balance – type "A".

Type "A" files are MS Excel files used for finding the system's balance due to water price variation. The system is lying at an initial status (balance) which is disturbed by WP increase and then successive steps are performed assisting the sizes to converge. Next, the calculations of the fluctuations of SIV components, WP, FWC and system's operating pressure are analyzed. The sizes involved in the "A" files are illustrated in Table 1.

Table 1. An example of a table.

Symbol	Appellation	Units
P_m	Average Operating Pressure	KPa
Q_{SIV}	SIV	m^3
Q_{TH}	Apparent losses Volume (theft)	m^3
Q_{RE}	Apparent losses Volume (reading errors)	m^3
Q_{UR}	Apparent losses Volume (under-registration)	m^3
Q_{ANB}	Authorised not-billed consumption Volume	m^3
Q_{REV}	Billed consumption Volume	m^3
Q_{NREV}	Non-Revenue Water Volume	m^3
C_{QSIV}	Water Cost per m^3 of SIV	€/m ³
C_{QREV}	Water Cost per m^3 of Q_{REV}	€/m ³

In order to find the pressure variation in relation with the WP variation, the hydraulic model is used. Initially, through elasticity of demand, the values of billed consumption are calculated for indicative WP values. Using the hydraulic model, the billed consumption's variation is simulated creating different node demand scenarios. SIV is calculated as the sum of real losses, apparent losses, authorized non-billed consumption and revenue water. At the first step of the process, the CARL value is measured by linear interpolation between known values for indicative

initial variations of WP. Next CARL moves between the two poles and reaches an average value. WP increase is considered to increase the illegal use and so the variation of this system's consumption component is correlated with WP and not with SIV. The volume of apparent losses, which constitute the reading errors, results from recording errors and transfer errors (to data bases etc). This SIV component is considered to be stable in type "A" files. The volume of apparent losses due to under-registration is adversely affected compared to pressure, but stays invariable in type A files (it changes in type B files). The authorized non-billed consumption is considered to vary in relation with pressure such as billed consumption. The revenue water varies according to the water price elasticity of residential, if the new WP is known. For each new WP change, the new revenue water volume is measured. Since the water price elasticity of demand depends on both the initial SIV and the WP variation, elasticity is calculated afresh in each step for the particular SIV level and for the particular WP change. NRW is calculated as the sum of the individual volumes of CARL, apparent losses and authorized non-measured consumption.

Full water cost depends directly on SIV and is calculated afresh for all the steps of the process (except for the first step). The total FWC was considered to vary according to the SIV variation, after the first step's increase which is the key assumption of the scenario. The water cost increase (per extra m³ entering the system) is observed when increasingly ever more damage is caused at the water resources or when water is abstracted from an even deeper level through boreholes. It can also observed water cost reduction (per extra m³ entering the system), when there is not any water resource damage and the production increase of water quantities reduces the expenses of the utility due to large-scale economy savings. The variation of WP after the first step, is associated with the variation of FWC_{it} and WP of the previous steps, so that it converges based on the FWCs. The significant balance factors converge to a balance point. The output data then enter the M file from which type "B" files receive them as input data. EARL is calculated in type B files.

2.2. Type "B" files.

Δημιουργήθηκε η εξίσωση (1) που υπολογίζει το νέο ποσοστό της τιμολογούμενης κατανάλωσης ως προς το R_{SIV} μετά από την συνολική μείωση του νερού λόγω διαχείρισης της πίεσης σε σχέση με την τελική εφαρμοζόμενη πίεση λειτουργίας. In type "B" files, EARL is calculated based on the new WP and the new FWC resulting from type "A" files. The Water Balance computation takes place for the first time after the pressure implementation at EARL levels in file B_0 . All the rest B_i files receive values from the central M file and calculate the above from the beginning. SIV is calculated to be equal to the amount of the initial SIV extracting the volume (R_{SIV}) by which it was reduced due to the PM interventions at EARL levels. The billed consumption depends on the SIV variation (already calculated) and the system's pressure. It is easy to measure the percentage of R_{SIV} concerning the billed consumption for the initial operating pressure. As long operating pressure is reduced so does the percentage of R_{SIV} which is part of billed consumption. In particular, when operating pressure is considerably reduced then certain activities last longer because they are also intertwined with the water volume (i.e. car washing, garden watering etc). Equation (1) was formed calculating the new percentage of the billed consumption related to R_{SIV} after the total water reduction due to pressure management in relation with the final operating pressure applied.

$$\frac{Q_{REV}}{R_{SIV}} = a_1 * e^{a_2 * P} \quad (1)$$

where a_1 and a_2 are coefficients depending on the initial percentage of (Q_{rev}/R_{SIV}).

The authorized non-billed consumption depends on pressure and varies according to Q_{rev} . The "illegal use" water volume depends only on the pressure change because there is no WP change in type "B" files. It changes according to Q_{rev} , such as the water volume corresponding to reading errors. The volume of apparent losses constituted by under-registration alters with opposite sign in relation with the pressure variation. This phenomenon is mostly observed for low pressures [8] and results from delaying starting flow of the hydrometer. This phenomenon depends on the operating pressure of the network and the hydrometers' age. Fontanazza et al [8] after conducting laboratory measurements defined the relation between the starting flow of a water meter with the network's pressure and the age of the water meter (equation 2). As they mention the correlation between the water meter' starting flow with the

network's pressure is linear and the correlation with the age of the meter is exponential. Fontanazza et al [8] presented laboratory results for the percentage of “under-registered” water volume related to SIV for different ages of water meters and for 4 different pressure values. Based on their results (the average value of the meters age was used) the variation of the “under-registered” volume related to the variation of the network's operating pressure was calculated and equation (3) was extracted.

$$Q_{start} = -0,7405 * P * e^{0,0031 * P + 0,00437 * Age} \quad (2)$$

$$\Delta Q_{UR} = 0,97 * \Delta P^{-0,197} \quad (3)$$

where Q_{start} is the starting flow of the water meter [lt/h], P is operating pressure [bar] and Age is the age of the water meter [years].

The equation connecting the available funds for pressure management interventions with the final operating pressure of the network (when PM is applied at EARL levels) will be derived from the relation between the cost of the interventions, whose results have been calculated through the model, and the operating pressure caused. If these points are depicted on a graph, a curve will be created. This curve should be able to expand for bigger amounts available but with reducing pressure up to a certain point beyond which no further reduction will be caused. Hence, equation (4) is applied to the whole range of interventions cost and is depicted in Figure 2.

$$P_m = \begin{cases} c_1 * \ln C_{TOTAL} + c_2, & \gamma I'_{PM} < C_{TOTAL} \\ (c_1 * \ln C_{TOTAL} + c_2) * C_{rd}^{C_{TN}}, & \gamma I'_{PM} < C_{TOTAL} < I''_{PM} \\ (c_1 * \ln C_{TOTAL} + c_2) * C_{rd}^{I''_{PMN}}, & \gamma I''_{PM} < C_{TOTAL} \end{cases} \quad (4)$$

where: P_m is operating pressure [KPa], C_{TOTAL} is the total cost of the interventions [M€] for achieving the specific SIV reduction, c_1 and c_2 are the coefficients resulting from the correlation, I'_{PM} is the total cost of the initial interventions [M€], C_{TN} is an index equal to C_{TOTAL} in integer [M€], I''_{PM} is the cost of interventions beyond which R_{SIV} does not vary [M€], I''_{PMN} is an index equal to I''_{PM} in integer [M€] and C_{rd} is a reduction factor and depends on P_m caused by the initial interventions.

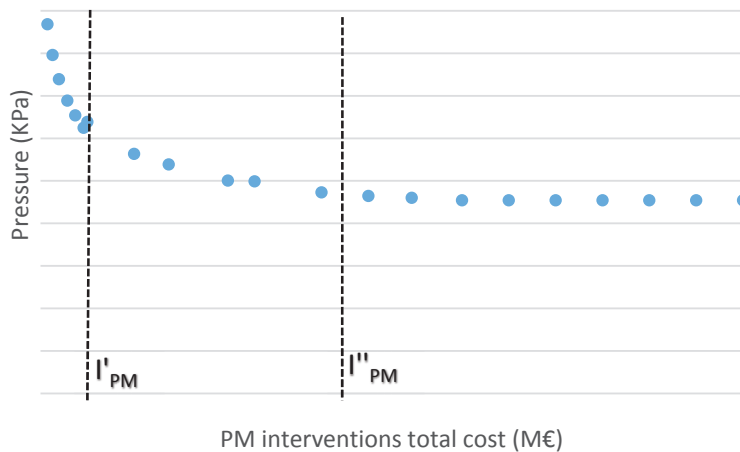


Figure 2. Graph of equation (4).

3. Implementation in Kozani WDS.

The last 3 years, at the city of Kozani (North Greece), the WDS hydraulic model was developed and the full water cost [9], the demand curve [10] and a pressure management study [11] were developed. Not only the economic benefits and the SIV reduction but also the expenses from a number of prioritized PM interventions were calculated (Table 2). Next all factors for PM implementation at EARL levels were calculated. The EARL for 5, 10, 15-years' time periods are calculated when the NPVs equals zero, which means at this point of the interventions implementation where the economic benefit due to SIV reduction (achieved through pressure management) is equal to the expenditures required. Then, based on Table 2, the logarithmic equation (5-first part) which connects the intervention cost with the SIV reduction was calculated reaching the final form of equation (5) applied to any amount of money available for interventions.

Table 2. Intervention costs and SIV reduction.

Interventions	SIV	SIV reduction		Cost per intervention	Total cost after each intervention
	(m ³ /day)	(m ³ /day)	(m ³ /year)	(€)	(€)
1 st Intervention	14,852	3,787	1,460,786	150,240 €	150,240 €
2 nd Intervention	14,217	635	231,603	107,427 €	257,667 €
3 rd Intervention	13,788	429	156,476	136,408 €	394,075 €
4 th Intervention	13,336	452	164,954	179,674 €	573,749 €
5 th Intervention	13,056	280	102,237	168,573 €	742,322 €
6 th Intervention	12,961	95	34,781	180,592 €	922,914 €

$$R_{SIV} = \frac{390.625 * \ln C_{TOTAL} + 3.058.004, \gamma \alpha C_{TOTAL} < 922.914}{(390.625 * \ln C_{TOTAL} + 3.058.004) * 0,986^{C_{TN}}, \gamma \alpha 922.914 < C_{TOTAL} < 9.000.000} \quad (5)$$

$$(390.625 * \ln C_{TOTAL} + 3.058.004) * 0,986^{C'_{PMN}}, \gamma \alpha 9.000.000 < C_{TOTAL}$$

Using equation (5) it is easy to calculate the SIV's annual reduction (when pressure management reduces the real losses at EARL levels) for each target year and for each value of marginal cost. The sizes of all SIV elements for two different cost estimations and for three different time periods of NPV calculation are presented in Table 3.

Table 3. Water volumes of DEYAK's Water Balance for 2011 when PM reduces the real losses at EARL levels.

SIV and its components	Initial Status	Water Volumes					
		PM implementation at EARL level (direct benefit)			PM implementation at EARL level (direct and indirect benefit)		
		(NPV 5-years)	(NPV 10-years)	(NPV 15-years)	(NPV 5-years)	(NPV 10-years)	(NPV 15-years)
<i>SIV</i>	6,921,387	4,680,220	4,386,967	4,276,782	4,270,684	4,105,520	6,921,387
<i>Q_{REV}</i>	2,555,472	2,247,507	2,207,210	2,192,069	2,191,231	2,168,536	2,555,472
<i>Q_{ANB}</i>	138,428	121,746	119,563	118,743	118,697	117,468	138,428
<i>Q_{TH}</i>	69,214	60,873	59,781	59,371	59,349	58,734	69,214
<i>Q_{RE}</i>	127,774	112,376	110,361	109,604	109,562	108,427	127,774
<i>Q_{UR}</i>	127,774	140,194	142,831	144,424	144,544	147,515	127,774
<i>CARL</i>	3,902,727	1,997,525	1,747,220	1,652,571	1,647,300	1,504,840	3,902,727

3.1. Example of 100% WP increase.

The process begins with an artificial increase of water price by 100% resulting from the water cost increase by 41.32% (from 7,835,967€ to 11,073,750€). The fact that an increase in water cost causes a higher WP increase is due to the non-billing of all SIV's m³. The WP applied will rise from 1.267€/m³ to 2.534€/m³ of revenue water. The system will balance after 6 steps due to the increase of WP and price elasticity of demand. This particular process takes place in file A₀, where the beneficial effect of PM implementation at EARL levels is not included. This PM implementation has a positive impact to all factors and should be analyzed afterwards. At Figure 3, WP and SIV variations during the switching of the various steps of the method are presented. Next in file B₁ the volumes of the

water consumed are calculated, such as the final pressure for the PM implementation at EARL levels, for a 15-years NPV and for considering the economic benefit not only as direct but as sum of both direct and potential indirect as well. Thereafter based on the new water volumes the FWC is calculated afresh in file M, and the computations of all type “A” and “B” files follow up to the point where there are not important variations, meaning the network's consumptions are in balance. Below are the graphs of the variation of the most significant sizes during the succession of steps (Figure 4).

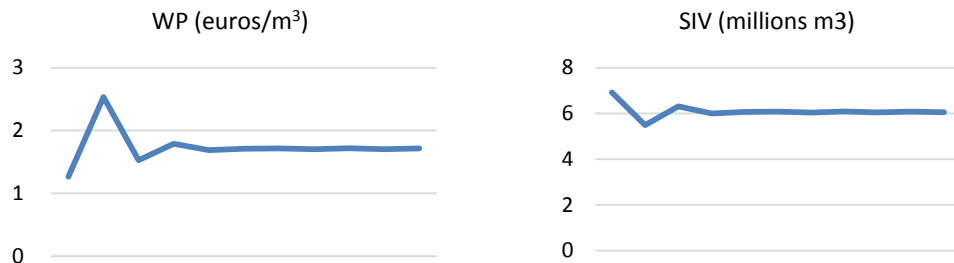


Figure 3: WP and SIV variations during the switching of the various steps of the method

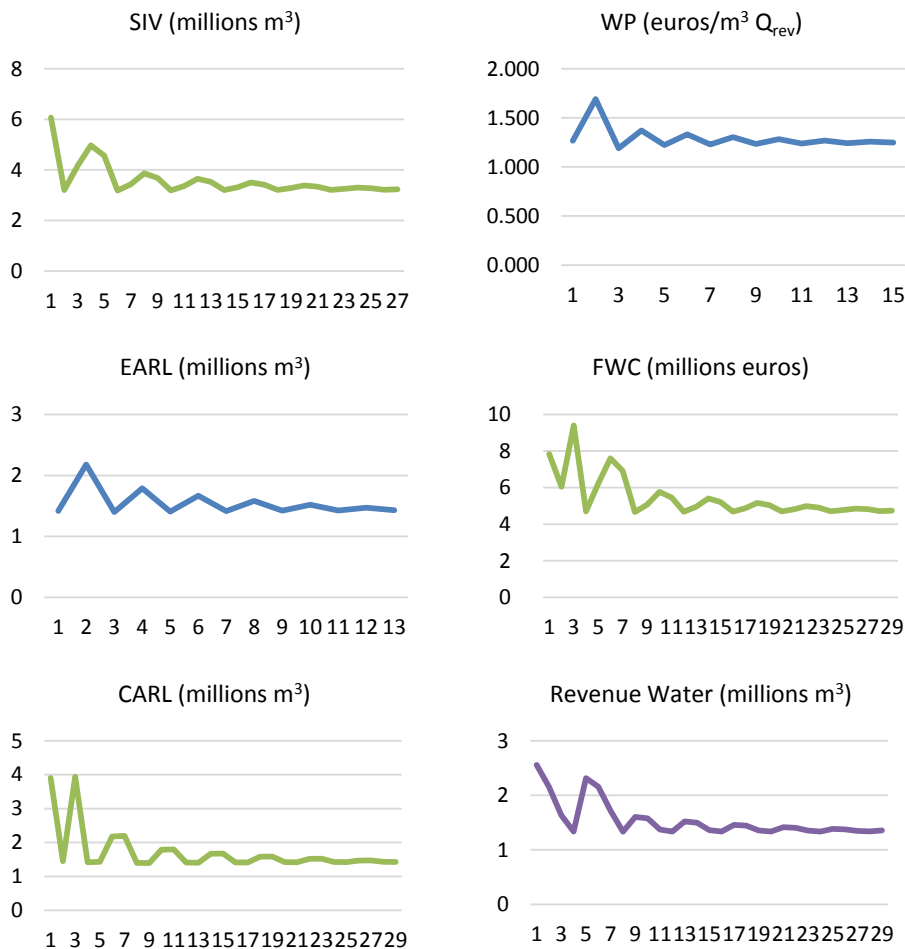


Figure 4: Variations of the most significant sizes of the system during the succession of the steps of the method

Table 4: The sizes of the system at sustainability level.

Sizes	Initial Status	First balance	Sustainability level	Sizes	Initial Status	First balance	Sustainability level
Pressure (KPa)	599.8	603.8	233	Billed use (m ³)	2,555,472	1,634,222	2,143,432
SIV (m ³)	6,921,387	6,066,541	3,988,598	NRW (m ³)	4,365,917	4,432,319	1,740,689
CARL (m ³)	3,902,727	3,939,636	1,423,287	FWC (€)	7,835,967	9,400,468	5,957,845
Illegal use (m ³)	69,214	97,780	55,534	FWC (€/m ³ Q _{SIV})	1.13	1.46	2.39
Reading errors (m ³)	127,774	127,774	104,478	FWC (€/m ³ Q _{REV})	3.07	6.26	2.78
Under-registration (m ³)	127,774	127,774	149,218	WP (€/m ³ Q _{REV})	1.267	1.690	1.247
Authorized non-billed use (m ³)	138,428	139,355	112,649				

The final step of the method is a reverse procedure. Based to the water balance price resulting from above (found equal to 1.247€), a disturbance of file A₀ occurs from the beginning considering B₁ balance sizes as input data. Now the sizes variation that will finally cause WP equal to 1.247€ is being searched. The values of these sizes express the system's sustainability level (Table 4).

4. Results and discussion

The results of the application of the methodology for WP changes by 100%, 200% and 300% are presented. In the first management scenario the WP increase is accompanied by PM implementation, while in the second case not. SIV is reduced in both cases. In first case, PM implementation at EARL levels and WP increase occur at the same time, while in second case only WP increase is performed. SIV variations are presented in Figure 5a. When simultaneous management implementation of both WP increase and PM implementation at EARL levels takes place, the volume of real losses decreases rapidly. During the implementation of the second management scenario (concerning only WP increase) the volume of real losses slightly increases. CARL variations are presented in Figure 5b. The volume of billed consumption decreases in both cases. When simultaneous management implementation of both water price increase and MP implementation at EARL levels occurs, a lower reduction of billed consumption is observed. When solely WP increase is implemented, the network's pressure is high, hence water volumes depending on high pressure and not being that beneficial are included in billed consumption. Therefore, the positive effect of PM implementation at EARL levels on billed consumption is multiplied. Revenue water variations are presented in Figure 5c. The full water cost where the system balances, when only water price increase is applied, is increased as expected for each higher initial WP increase. At this point, it should be stated that the incoming water cost per m³ is increased in proportion to the SIV increase. As a result, by SIV reduction, FWC decreases directly. In this case as the benefit resulting from the SIV reduction is not enough to cover the initial increase of FWC, the final FWC increase is observed. In the case of PM implementation at EARL levels, FWC decreases due to high SIV reduction, which overcomes the initial increase of FWC and WP. FWC variations are presented in Figure 5d.

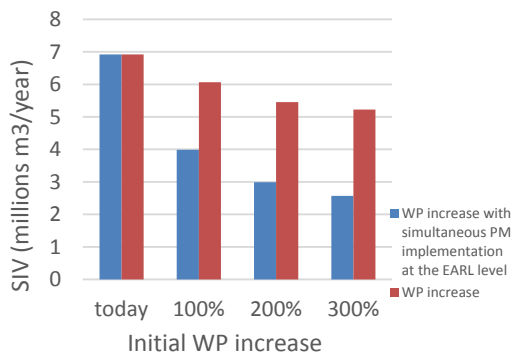


Figure 5a: SIV vs initial WP increase

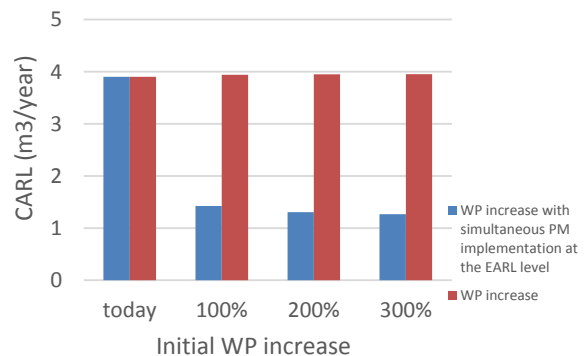


Figure 5b: CARL vs initial WP increase

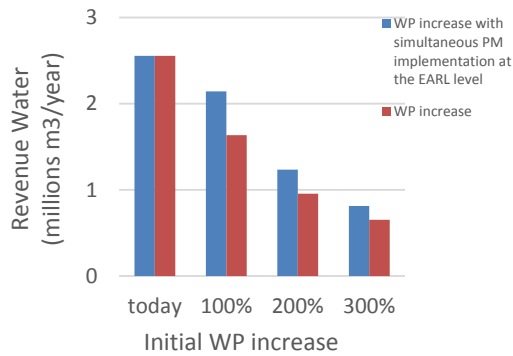


Figure 5c: Revenue Water vs initial WP increase

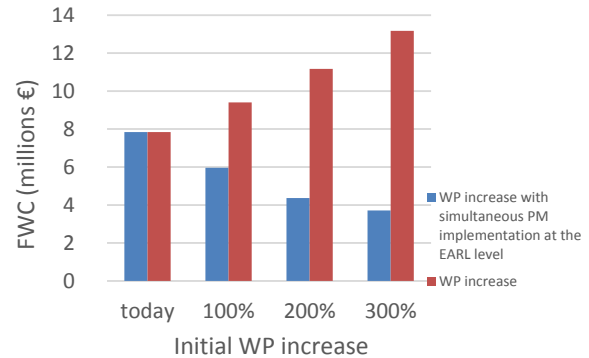


Figure 5d: FWC vs initial WP increase

WP in which the system balances, when only water price increase takes place, is increased as expected for each higher initial increase of WP. In case of PM implementation at EARL levels, WP not only is increased with lower rate but also the system balances at the reduced price of 1.247€ for initial WP increased by 100%. WPs are shown in Figure 6a. Operating pressure is increased slightly due to the reduction of billed consumption during the individual WP increase. In case of PM implementation at EARL levels the average pressure decreases dramatically arriving at 224 KPa when initial water price is increased by 300%. Pressure values are shown in Figure 6b.

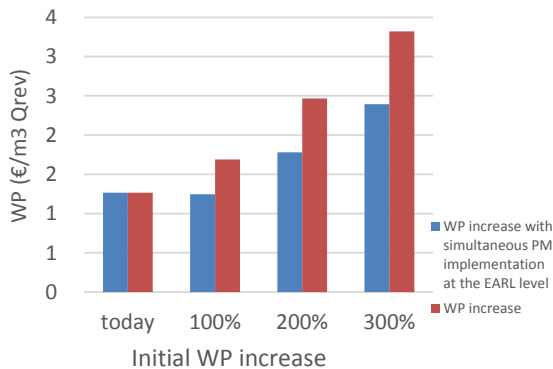


Figure 6a: Final WP vs initial WP increase

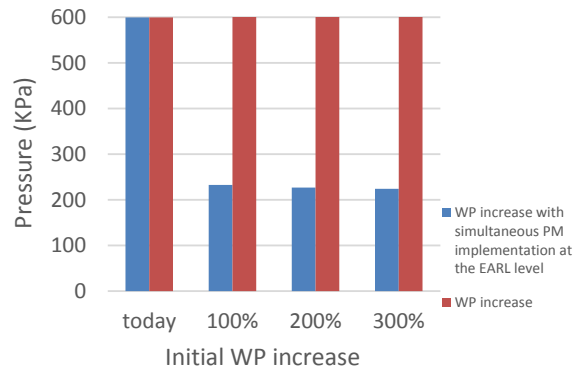


Figure 6b: Pressure vs initial WP increase

5. Conclusions

The present study fills a gap in the WDS management. Specifically, a mechanism of finding the balance of the components of system consumption, the operating pressure, the cost of water and most importantly the WP in case of increase full water costing implementation, is presented. In this case, it is necessary to implement NRW (especially real losses) reduction measures to alleviate consumers, who is expected to be prejudiced by a WP increase. It is important to calculate the network's varying factors to the point where the EARL level occurs. In this paper, a methodology of calculating SIV components and other factors (pressure etc.) of the network when PM is implemented at the EARL level, is analyzed.

There are presented scenarios of 100%, 200% and 300% increased WP, without and with simultaneous PM implementation at the EARL level. PM implementation at the EARL level helps system's sustainability resulted benefits to all water users (and the environment as well). When simultaneous WP increase and PM implementation at EARL levels took place, the CARL decreased rapidly, while during the implementation of the "WP increase" management scenario CARL slightly increased. The positive effect of PM implementation on revenue water is resulted. In the case of PM implementation at EARL levels, FWC decreases due to high SIV reduction, which

overcomes the initial increase of FWC and WP. In case of PM implementation, WP is increased with lower rate. For initial WP increased by 100%, the system balances at a WP even lower from the initial one. In case of PM implementation at EARL levels the average operating pressure decreases dramatically.

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